Aiding Vertical Guidance Understanding

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ABSTRACT

A study was conducted to evaluate training and displays for the vertical guidance system of a modern glass cockpit airliner. The experiment was performed in a fixed-base simulator that was used to run a complete flight with airline pilots. Three groups were used to evaluate a new flight mode annunciator display and vertical navigation training. Results showed that pilots did better when they had the training and even better when they had the training and the Guidance-Flight Mode Annunciator. Using actual behavior of the avionics to design pilot training and FMA is feasible and yields better pilot performance.

Keywords

Vertical Navigation, Pilot understanding, Automation Surprise, Flight Management, Cognitive Engineering, Human Factors, Simulator, Flight Mode Annunciator

INTRODUCTION

Studies of pilot understanding about flight deck automation have indicated that they are uncomfortable with auto flight systems and that these systems are probably the least understood aspect of automation in modern jets. Wiener [1] provided evidence that identified the autoflight system as one that pilots did not understand well. In his study, he asked almost 300 pilots to rate their agreement with the following statement: "In the Boeing 757 automation, there are still things that happen that surprise me." Results indicated that about 55% of the pilots agreed with that statement. About 30% of the pilots agreed with a second statement, "There are still modes and features of the B-757 that I don't understand."

Sarter and Woods [2] replicated Wiener's findings. In their study, 67% of pilots agreed with the surprise statement that was mentioned above. They also showed that 40% of the pilots in their study agreed with the second statement about not understanding the airplane's modes and features completely. Pilots attributed their lowered understanding of vertical navigation to their inability to visualize the vertical path that the airplane was flying, difficulty in predicting vertical navigation behavior, and due to an incomplete understanding of the system.

Training

Hutchins [3] reports that training often lacks a robust conceptual and theoretical component. Line pilots are taught one method for solving a problem or how to apply the automation. They are not normally taught that there are alternative methods to do the same task or how these different methods interact. Additionally, current training seems to be based on rote memorization of procedures and performance data. Training consists of explaining when to perform a task and what should happen as a consequence. This type of training leaves much to be desired and has prompted several airline pilots to want to know more. Pilots would like to be able to ask and get answers for the following questions: "What problems does this solve?", "When would I use this?", and "How does this help me to solve this problem that I am facing?"

Hutchins also suggests that training pilots in the conceptual framework of the airplane and its behavior should actually decrease training time. He proposes that retention is much better when what is learned can be integrated into a conceptual framework. This is a basic tenant of training system design and should find its way into pilot training programs.

An example is the current training for glass-cockpit aircraft. When students without glass experience are brought into classes, they are immediately exposed to procedures and task-response pairs. A first step may be to acquaint students with an overall conceptual understanding of the glass cockpit, how it uses computer technology to optimize the flight path, and an understanding of the different flight modes [3].

Crowther, Chappell, and Mitchell [4] suggest that pilots need an accurate and complete system knowledge to ensure that pilots do not misunderstand avionics modes. They presented a methodology for presenting the vertical navigation information to the pilot in a computer-based training situation. Pilots were given a display of the vertical path of the airplane along with specific mode information and predictions of future modes. The results suggest that this type of information enhances a pilot's awareness of vertical guidance modes.

The Cockpit System

Current glass cockpit aircraft use annunciation schemes that were designed based on the displays found in an earlier generation of avionics systems (i.e., DC-10 and B-727). This earlier generation of avionics displayed the results of navigation, control, and stability augmentation tasks only. Because guidance was not automated, it was not annunciated on a cockpit display.

In the latest generation of airplanes, navigation, control, and flight planning tasks are partially annunciated and trained. Adding to the complexity is the integration of the autopilot and autothrottle, which provides the aircraft with many advanced functions. These advanced functions need to be understood in a timely manner to be fully utilized. This paper refers to the understanding of the autopilot/autothrottle task as the guidance task.

The *Guidance* task compares the actual position of the aircraft to the current leg of the lateral and vertical flightplan to generate a set of targets and control-modes. Targets include aircraft heading, altitude, speed, flight-path angle, vertical speed, and thrust. Control-modes define the parameters that are controlled to achieve these targets. Lateral axis control-modes, such as heading, adjust the aircraft roll and yaw to maintain the aircraft along a target heading to the next waypoint. Vertical axis control-modes define the position of the elevators and throttles to control the altitude of the aircraft. In current generation aircraft, the control task is annunciated, while the guidance task is not directly annunciated. . Also, guidance is not treated as a separate topic in training, although a limited amount of information about the guidance function can be found in the latest editions of the FMS reference manuals for the MD-11, A-320, A340, B-777, and B-747-400. There is a lack of distinction between guidance and control functions in the research community, with a few exceptions (Abbott and Rogers [8]). Rather, researchers tend to merge the guidance and control tasks under the topics of avionics modes, mode awareness, and annunciation (e.g., Billings, [5]; Hutchins, [3]).

The state of the guidance task can be inferred by integrating information from the primary flight display, the flight mode annunciator, navigation display, and various control display unit pages. However, pilots do not receive the necessary training to make these complex inferences about the avionics and integrating the information is a difficult process without this training.

Control FMA Design

The design of the existing MD-11 FMA is shown in Figure 1. The two main speed control modes are Pitch and Thrust. In a Pitch speed control mode, changing the pitch of the airplane, with a constant thrust setting controls the airspeed.

The Altitude Control mode can be viewed as the converse of the Speed Control mode. Figure 1 shows speed as controlled by Pitch, which therefore leaves altitude to be at a constant, Climb Thrust setting while climbing to the altitude target. If speed were controlled by thrust, the altitude target would be reached by varying the pitch.

An example of this is a Vertical Speed climb, which specifies the rate at which the airplane climbs and holds a target airspeed by varying thrust. These annunciations are presented in combinations. Possible annunciations for descent are either “Pitch” and “Idle,” or “Thrust” and “V/S.” The combinations “PITCH” and “PROF,” or THRUST” and “IDLE” will never be seen. These combinations of annunciations may not be exclusive either. For example, “PITCH” and “IDLE” are used as the annunciation for more than 3 different aircraft behaviors.

Guidance FMA Design

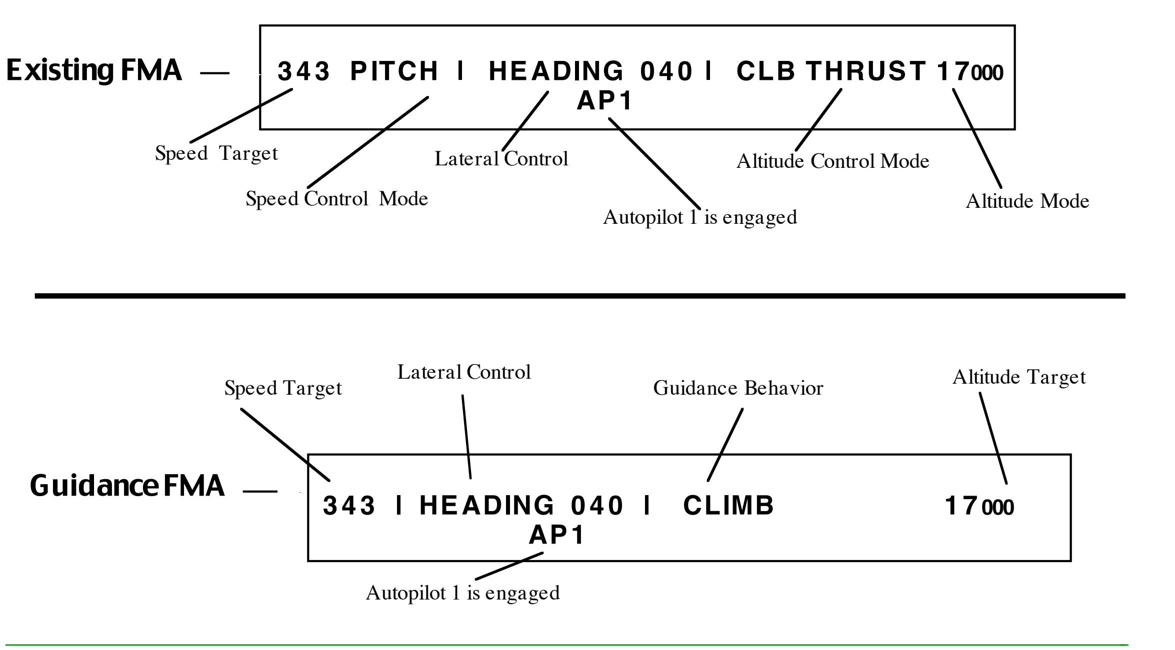
The Guidance FMA presents the automated vertical flight mode information differently. Instead of having two modes that give information about how the aircraft is being *controlled*, which require a translation to interpret the behavior of the aircraft, the Guidance FMA uses one annunciation that describes the overall vertical behavior of the aircraft. The behavior names simplify the vertical guidance logic by eliminating the transformation from the control mode information to the behavior. Under normal automated operations, this overall behavior name consists of one of the following:

- **Climb**
- **Climb Intermediate Level**
- **Cruise**
- **Descent**
- **Early Descent**
- **Late Descent**
- **Descent Intermediate Level**
- **Descent Overspeed**

Most of these labels have an intuitive meaning to pilots, but a few require a deeper understanding of the vertical guidance system. In these cases, if the pilot does not understand the meaning of the annunciation, it is difficult to ignore.

Another benefit of the Guidance FMA behavior label is that the pilot only has to view the FMA to find out what mode of operation the system is in. With the existing FMA, the pilot knows that the plane is in descent when the speed mode is in idle, but there is no information provided as to whether the plane is short or long of the path. To find this information, the pilot has to go to the performance page on the CDU and monitor the path error information. With the Guidance FMA, either a “Late Descent” or an “Early Descent” display provides that information directly.

Knowing the behavior name also assists pilots with predicting the next vertical modes because of the generally accepted sequence of events during a normal flight. Typically, Climb will go to Cruise or Climb Intermediate Level. Climb Intermediate Level, will then proceed to Climb once the airplane is cleared to a higher altitude.



Diagrams showing the existing MD-11 FMA and the guidance model. Note: Presentation on the Primary Flight Display is white or magenta text on black background.

Method

An experiment was conducted to evaluate both a new Flight Mode Annunciator and a training package to accompany the new display. The annunciator and training material were derived from a formal methodology used for requirements specification, known as the Operational Procedures Model [6]. The content for the model came from a representation of the actual vertical guidance logic.

The study used three conditions so that adequate control could be established for comparison. Current MD-11 pilots with at least one year of experience on the airplane were used as subjects in the three conditions. The Control condition consisted of pilots who came in and flew the simulation without training and with the existing FMA on the MD-11. This condition provided a baseline of how pilots fly with the current training and experiences. The second condition, Training, allowed subjects to complete a training program on vertical guidance techniques. This training explained how to read current FMA displays and how to infer the behavior of the airplane from the displayed information. In the third condition, Display, the subjects went through the training program and then flew the scenario with the new Guidance FMA display. The control and training groups used the existing MD-11 displays for their flight scenarios.

Experimental Subjects

Twenty-seven MD-11 pilots participated in the study. Participants were randomly assigned to conditions. There were 11 Captains and 16 First Officers that participated.

Training

Participants were given a tutor that was developed to provide an overview of the vertical navigation concepts, an introduction to the operational procedures for normal operations and to increase understanding of the MD-11 system (Feary et al., [7]). The following Vertical Guidance topics were covered in the tutor:

- **Flight Mode Annunciator**
- **Glareshield Control Panel**
- **Altitude Change Methods**
- **Optimum Altitude Selection**
- **Flight Phases**
- **Vertical Guidance Operations**
- **Vertical Profile Performance**
- **Descent Performance Changes**

Training was given to subjects in the Training and Display conditions only and presented on a laptop computer. Training took approximately 1.5 to 2 hours to finish.

The training in the Display condition showed the new Guidance FMA in all of the Flight Mode Annunciator pictures. For the Training condition, regular MD-11 FMAs were used. All of the training materials, graphs, and other information were the same for the two conditions.

Experimental Flight

A Line-Oriented Flight Scenario was developed to test pilot understanding. The flight was from Portland to Seattle and took advantage of the Seattle FMS transition into runway 16R. For each flight, the pilot was designated as the Pilot Flying, while the experimenter was the Pilot Not Flying and source of Air Traffic Control Information. The pilot was instructed at the beginning of the flight that they were to keep the system in full automatic mode for as long as possible enroute. The experimenter set up the airplane configuration and the FMS for departure.

Using a variant of the SAGAT technique, the simulator was stopped at eight points during the flight. These eight points were selected as points during which a significant transition in the vertical guidance was occurring. If the points had been selected at random, as the SAGAT technique suggests, it is likely that most of these transitions would have been missed. At each of these points we asked 3 types of questions to measure pilots understanding of the avionics. The questions consisted of:

- Pick the targets and behaviors which best describe the current situation of the airplane.
- Pick the targets and behaviors which best describe the future situation of the airplane.
- What will the FMA display next?

MD-11 Simulator

The simulator did not display the outside environment and it did not have any motion capability. Pilots remarked that the simulator was similar to a real MD-11 and there were no shortcomings noted in terms of displays or controls for the pilot tasks.

Data Collection

At each stop in the scenario, pilots were asked to fill out a form asking them to identify the origins of the current speed and altitude targets. Additionally, we asked them to identify the behavior of the aircraft. At each stop, we asked pilots to do this for the current situation and for the next event in the scenario.

An FMA Template device used a series of push/pull slide rules so that pilots could construct the FMA for the next flight event in the simulation. To do this, pilots moved the scales up or down until the correct word or value appeared in the window.

Results

A difference was noted in the amount of time that the three experimental groups had logged on the MD-11. The control group reported a mean of 1672 hours, the training group, 1022 hours, and the display group, 604 hours. This difference was significant ($df = 2, 24$, $F = 3.96$, $p < 0.04$). The participants were randomly assigned to conditions, so this difference in experience was a coincidence.

The most important finding was that pilots in the Guidance FMA condition could predict the future state of the avionics better using the FMA Template than could the Control or Training conditions. Pilots had a better understanding of the avionics and used the displayed information to help them to predict what the future FMA. The difference between the Training group and the Control group was not significant. Overall performance scores were 91% correct for the Guidance FMA Condition, 86% for the Training condition, and 79% for the Control condition (added over all stops, higher number indicates more answers correct).

The flight quiz data showed that there were significant differences when looking at all of the categories combined (composite index). The Guidance FMA group showed better performance across these measures, which support the notion that the understanding of the vertical guidance procedures was enhanced with the Guidance FMA and with training.

The analysis of differences between the current and future aircraft behavior using the flight quiz measure also proved interesting. Pilots were asked to describe the current and next situations in terms of altitude target, speed target, and airplane behavior. The summaries for the current situation quiz showed that the composite index data (addition of altitude, speed and behavior scores) and the behavior data were significantly different when comparing the Guidance FMA group to the Control group. Mean scores for the three groups (Guidance-FMA, Training, and Control) on the composite index were 80%, 70%, and 64%, respectively.

For the next or future situation flight quiz, we found that pilots in the Guidance FMA condition performed better than pilots in the Control group. On the composite index for the next situation flight quiz, pilots in the Guidance-FMA condition scored 83%, pilots in the Training condition scored 77%, and pilots in the Control Group scored 79% correct. This indicated that groups that had the display and training were more accurate at predicting what the avionics would do next than was the control group.

A questionnaire was given to pilots in the display and training conditions to rate the characteristics of the tutor. Overall, 12 of 18 pilots in training conditions thought the training was good or excellent. They liked the feedback and thought it was presented in a timely manner. Pilots also recommended that the training be used in both initial and recurrent training.

We asked pilots in the Display condition to rate the Guidance FMA in comparison to the existing MD-11 FMA on seven rating scales. Results indicated an overwhelming acceptance of the new display. Pilots felt the information was directly usable, helped to understand the current modes, and helped them to feel more confident about what the avionics was doing. Most pilots reported that they would like to see the Guidance FMA on the MD-11.

A problem that pilots had with the Guidance FMA was that they felt a bit uncomfortable with removing the thrust and pitch annunciations from the speed FMA. Some of this discomfort may be accounted for by familiarity with the speed mode annunciation, but it was not elaborated. Further investigation is required to determine if there are situations during mixed mode (i.e. autopilot on/autothrottle off) flight for which the speed mode annunciation would aid understanding of the aircraft behavior. All of the other comments were positive.

Discussion

The Guidance FMA emerged as the superior condition in this study. Looking at the objective data, we found that pilots in this condition could describe the current behavior and predict the next mode of operation better than the control group for normal, automated operations. Pilots in the Guidance FMA group were also better at constructing the next FMA when compared to the control group. The combination of training the pilot on what the vertical navigation system is doing and then displaying that information resulted in the best demonstration of pilot knowledge of the three groups. This may be a reflection of better understanding the avionics, more descriptive annunciation, or both, given the types of questions that were asked.

The data obtained from the subjective questionnaire showed that pilots liked the display. Pilots stated that it was easier to understand what the airplane was doing and to predict what the next FMA would look like. They also felt that the Guidance FMA was usable and made them more confident in their understanding of the avionics, while reducing automation surprises during normal automated operations.

Pilots in the Guidance FMA condition had significantly fewer hours in the airplane than did pilots in both the training and control groups. This is an interesting finding because it indicates that we might have found even better understanding if we had equated the groups on experience. This finding also points to the need for having a Guidance FMA and advanced training available for pilots to get them up to speed and performing better with less hours in the airplane than pilots without this display and training combination.

It is not clear how much training adds to the pilots understanding of the avionics from the current experiment. There were trends for training being a positive influence, but this was not statistically significant as calculated with post-hoc, pair-wise comparison tests. For each of the measures of understanding, the display group was significantly better, with the training group having a higher means than the control group. This indicates that both are necessary to really make an impact on the pilot. It is not just enough to train pilots in the operation of the airplane, but they must also have a display that relates this knowledge back to the task.

In the display condition, pilots understood the workings of the airplane at a much higher level. We also found that this understanding applied to future understanding of airplane states. This is a powerful combination and one that can lead to improved understanding on the part of the pilots. This understanding also can be obtained earlier in the learning curve for the airplane. These findings suggest that improved results may also be found for abnormal conditions, including automation failures, semi-automated, and mixed-mode flight, but this will need to be further investigated.

The findings also help the pilot to better understand the three questions posed by Wiener [1]: "What is it doing?" "Why did it do that?" and "What will it do next?" These three questions were the most frequent that were heard in glass cockpits by pilots trying to figure out how the avionics were operating. The first question relates to the present condition of the airplane, the second to how it got into that condition, and the third to a future state of flight. Our study showed that by training pilots and giving them the Guidance FMA, they were better able to answer these questions. This level of understanding could be further enhanced with additional situation description aids, such as Vertical Profile Displays. The more knowledge that pilots have about the avionics, the less chance for an automation surprise and a greater chance for the pilot to feel that they understand what is happening at all times and to be comfortable with the monitoring task that they are performing in automatic flight options.

References

1. Wiener, E.L. (1989). *Human factors of advanced technology ("glass cockpit") transport aircraft.* (NASA Contractor Report No. 177528). Moffett Field, CA: NASA ARC.

2. Sarter, N. & Woods, D. (1992). Pilot interaction with cockpit automation: Operational experiences the Flight Management System. *International Journal of Aviation Psychology,* 2(4), 303-321.

3. Hutchins, E. (1996). Immediate mode management interface final report. NASA Ames Research Center. Hutchins, 1996

4. Crowther, E.G., Chappell, A.R., and Mitchell, C.M. (1994). *VNAV tutor: System knowledge training for improving pilot's mode awareness*. Paper presented at the 1994 IEEE International Conference on Systems, Man, and Cybernetics. San Antonio TX, October.

5. Billings, C. E. (1997). Aviation automation: The search for a human-centered approach. Mahwhad, NJ: Lawrence Erlbaum.

6. Sherry, L., & Polson, P. G. (1996). Annunciation and training of knowledge-based avionics (Pub no. C69-5370-003). Phoenix, AZ.

7. Feary, M., Alkin, M., Palmer, P., Sherry, L., McCrobie, D., & Polson, P. (1997). Behavior-based vs. system-based training and displays for automated vertical guidance. In Proceedings of the Ninth International Symposium on Aviation Psychology. Columbus, OH.

8.Abbott, T.S., & Rogers, W.H. (1993). Functional Categories for Human-Centered Flight Deck Design. NASA Langley Research Center. Hampton, VA.